

EO-1/Hyperion hyperspectral imager design, development, characterization, and calibration

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ABSTRACT

The Hyperion Imaging Spectrometer is one of three principal instruments aboard the EO-1 spacecraft. Its mission as a technology demonstrator is to evaluate on-orbit issues for imaging spectroscopy and to assess the capabilities of a space-based imaging spectrometer for earth science and earth observation missions. The instrument provides earth imagery at 30 meter spatial resolution, 7.5 km swath width in 220 contiguous spectral bands at 10 nm spectral resolution. Spectral range is from 0.4 μm to 2.5 μm . The instrument includes internal and solar calibration sub-systems. This paper will review the design, construction and calibration of the Hyperion instrument. The on-orbit plans and operations will be presented along with updated calibration and characterization measurements.

1. INTRODUCTION

The EO-1 mission is part of the NASA New Millenium Program and is focused on new sensor and spacecraft technologies that can directly reduce the cost of Landsat and related Earth Monitoring Systems. The EO-1 satellite will be in an orbit that covers the same ground track as Landsat 7, approximately one minute later (Figure 1-1). This will enable EO-1 to obtain images of the same ground areas at nearly the same time, so that direct comparison of results can be obtained for Landsat-ETM+ and the three primary EO-1 instruments. Following EO-1, in nearly the same orbit, are SAC-C (an Argentinean satellite) and TERRA. The four satellites constitute the “morning constellation.”

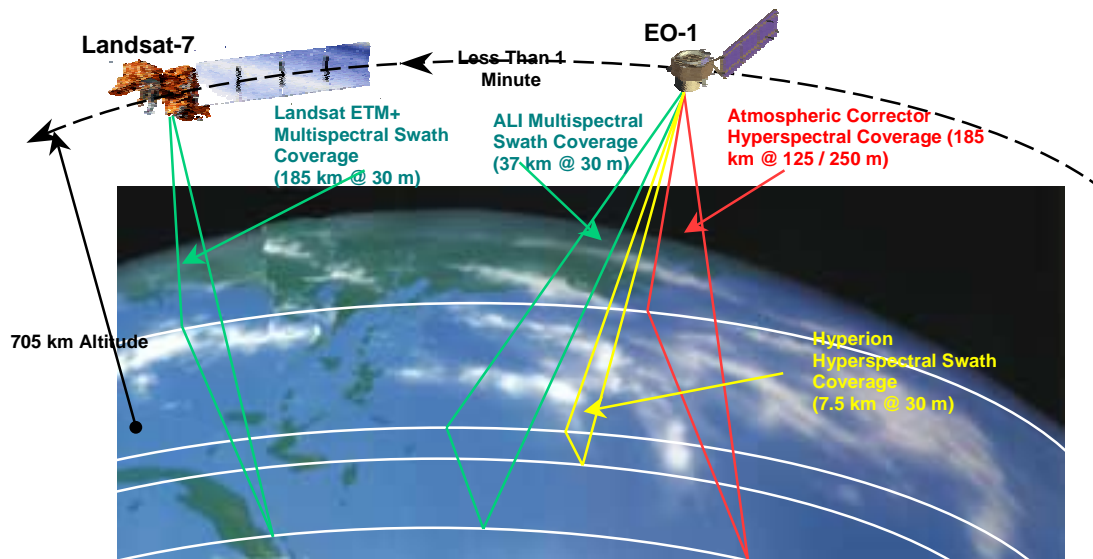


Figure 1-1– A view of the Earth with EO-1 above showing instrument swath widths

The three primary EO-1 instruments are the Advanced Land Imager (ALI), the Hyperion and the Linear etalon imaging spectrometer array Atmospheric Corrector (LAC). An overview of the operations scenario for these three instruments is given in Figure 1-1. A summary of the three instrument characteristics is given in Figure 1-2 and a photograph of the spacecraft with the instruments on the nadir deck is given in Figure 1-3. ALI is a calibrated, multi-spectral system consisting of a 15° Wide Field Telescope (WFT) and partially populated focal plane, occupying 1/5th of the traditional field-of-view Landsat. This gives a ground swath width of 37km. Hyperion is a grating imaging spectrometer having a 30-meter ground sample distance over a 7.5 kilometer swath and providing 10nm (sampling interval) contiguous bands of the solar reflected spectrum from 400-2500nm. LAC is an imaging spectrometer designed to monitor the atmospheric water absorption lines for correction of atmospheric effects in multispectral imagers such as ETM+ on Landsat. This paper focuses on the Hyperion Instrument.

Parameters	MULTISPECTRAL	HYPERSPECTRAL	
	ALI	HYPERION	LAC
Spectral Range	0.4- 24 μ m	0.4- 2.5 μ m	0.9- 1.6 μ m
Spatial Resolution	30 m	30 m	250 m
Swath Width	37 Km	7.5 Km	185 Km
Spectral Resolution	Variable	10 nm	2-6 nm
Spectral Coverage	Discrete	Continuous	Continuous
Pan Band Resolution	10 m	N/A	N/A
Number of Bands	10	220	256

Figure 1-2 – Summary Of Primary EO-1 Instrument Characteristics.

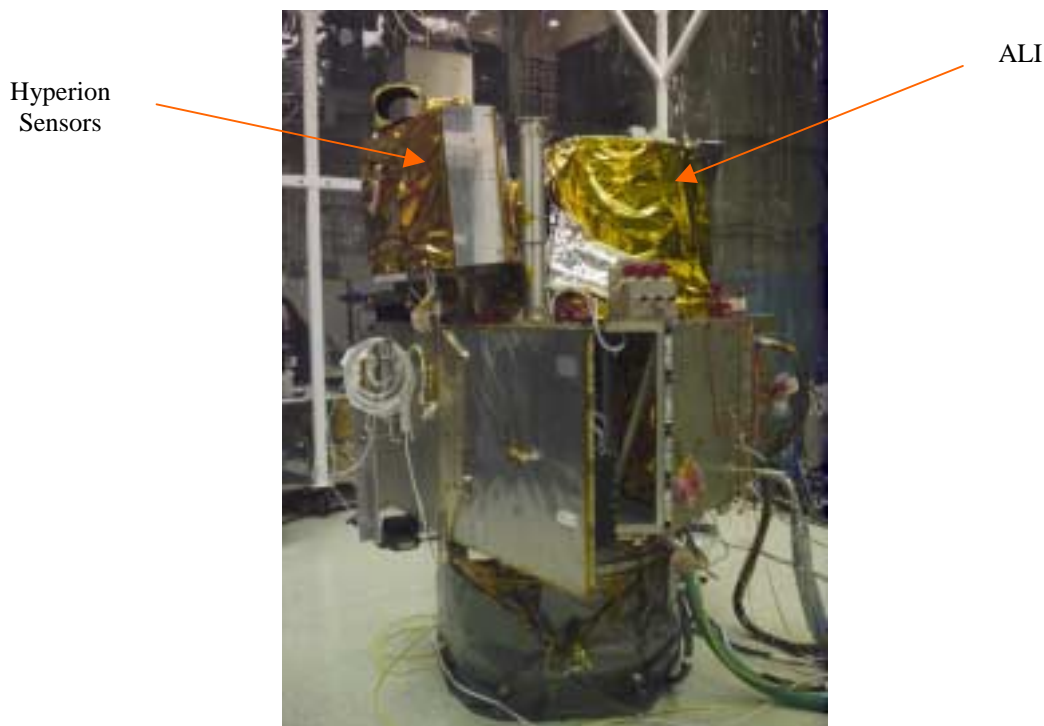


Figure 1-3 – EO-1 Spacecraft with sensors mounted on the nadir deck.

2. HYPERION SYSTEM DESCRIPTION

The Hyperion instrument provides high quality calibrated data that can support evaluation of hyperspectral technology for Earth observing missions. Key instrument performance characteristics are shown in Figure 2-1. The Hyperion is a “push broom” instrument. Each frame of imagery taken in this push broom configuration captures the spectrum of a line 30m align the in-track direction by 7.5Km in the crosstrack direction. Hyperion has a single telescope and two spectrometers, one visible/near infrared (VNIR) spectrometer and one short-wave infrared (SWIR) spectrometer.

Instrument Parameter	Hyperion Instrument Characteristic
GSD at 705 km Altitude	30 m
Swath Width (km)	7.5 km
Spectral Coverage	0.4 - 2.5 μm
Imaging Aperture	12.5 cm diameter
On-orbit Life	1 year (2 years goal)
Instantaneous Field of View	42.5 μrad
Number of Spectral Channels	220
Spectral Bandwidth	10 nm
Cross-track Spectral Error	<1.5 nm (VNIR), <2.5 nm (SWIR) (TBR)
Spatial Co-registration of Spectral Bands	<20% of Pixel (TBR)
Absolute Radiometric Accuracy	<6% (1 sigma)
Data Quantization	12-bit
Instrument Weight	49 kg
Instrument Power Consumption	78 Watts Orbit Average

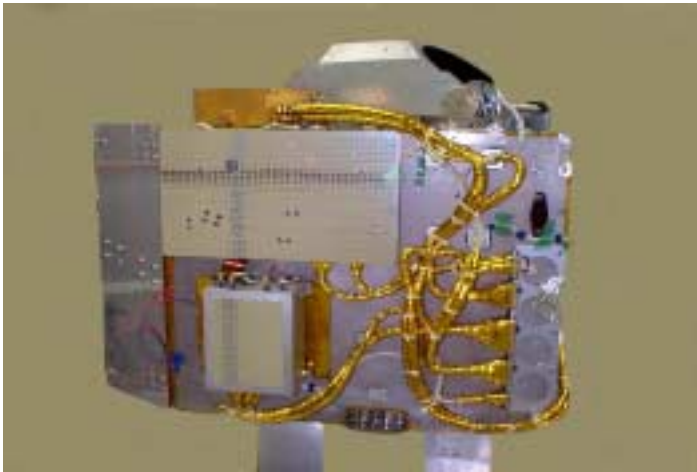
Figure 2-1. Hyperion key performance characteristics

The Hyperion instrument consists of three physical units (Figure 2-2): (a) the Hyperion Sensor Assembly (HSA); (b) the Hyperion Electronics Assembly (HEA); and (c) Cryocooler Electronics Assembly (CEA). The HSA includes the optical systems, cryocooler, in-flight calibration system and the high-speed focal plane electronics. The HEA contains the interface and control electronics for the instrument and the CEA controls cryocooler operation. These units are placed on the deck of the spacecraft with the viewing direction along the major axes of the spacecraft. (See Figure 1-3)

The Hyperion Sensor Assembly (HSA) includes the telescope, the two grating spectrometers and the supporting focal plane electronics and cooling system (See Figure 2-3). The Hyperion telescope (fore-optics) is a three-mirror anastigmat design. All of the mirrors in the system along with the structure holding the optical elements are constructed from aluminum, providing an athermal optical design. In operation, the housing will be maintained at $20^{\circ} \pm 2^{\circ}\text{C}$ to minimize temperature gradients in the metering structure.

The Hyperion telescope images the Earth onto a slit that defines the instantaneous field-of-view which is 0.624° wide (i.e., 7.5 Km swath width from a 705 Km altitude) by 42.55 $\mu\text{radians}$ (30 meters) in the satellite velocity direction. This slit image of the Earth is relayed to two focal planes in the two grating imaging spectrometers. A dichroic filter in the system reflects the band from 400 to 1,000nm to one-spectrometer (VNIR) and transmits the band from 900 to 2,500nm to the other spectrometer (SWIR). The VNIR and SWIR spectrum overlap from 900 to 1000nm will allow cross calibration between the two spectrometers. Both spectrometers use an Offner optical configuration with a convex grating on the secondary element. The gratings were manufactured by the Jet Propulsion Laboratories.

The visible/near-infrared (VNIR) spectrometer has an array of $60\mu\text{m}$ pixels created by aggregating 3×3 sub-arrays of a $20\mu\text{m}$ CCD detector array. The VNIR spectrometer uses a 60 (spectral) by 250 (spatial) pixel array, which provides a 10nm spectral bandwidth over a range of 400-1000nm. The short wave infrared (SWIR) spectrometer has $60\mu\text{m}$, HgCdTe detectors in an array of 160 (spectral) x 250 (spatial) channels. Similar to the VNIR, the SWIR spectral bandwidth is 10nm. Thus, the spectral range of the instrument extends from 400 to 2,500nm with a spectral resolution of 10nm. The HgCdTe detectors in the SWIR spectrometer are cooled by an advanced TRW cryocooler and are maintained at 115 K during data collections.



Hyperion Sensor Assembly (HSA)



Hyperion Electronics Assembly (HEA)



Cryocooler Electronics Assembly (CEA)

Figure 2-2 – The Hyperion Instrument

A common on-board calibration system is provided for both the VNIR and SWIR spectrometers. Redundant calibration lamp sets produce reference signals to monitor detector performance following image acquisition. The calibration lamp sources are placed on an absolute radiometric scale during ground calibration, then cross-referenced against both solar and lunar calibrations during on-orbit operations. The solar calibration utilizes a diffuse reflector on the backside of the optical cover to provide uniform illumination across the focal plane arrays. For the solar calibration, the cover is set at a 37-degree angle and the spacecraft is oriented such that the sun enters the solar baffle normal to the earth viewing direction. Solar and in-flight calibration data will be used as the primary source for monitoring radiometric stability, with ground site (vicarious) and lunar imaging treated as secondary calibration data.



Figure 2-3 – Hyperion Sensor Assembly (HSA)

The HSA is interfaced with two electronics boxes, the Hyperion Electronics Assembly (HEA) and the Cryocooler Electronics Assembly (CEA). The HEA has six electronic boards for control and data formatting. These include: a formatter board for

timing synchronization with image data reformatting; a processor board that controls instrument operations; a telemetry board for receipt and conditioning of housekeeping data; a transceiver board for interface with the spacecraft computer; and boards for power and motor/lamps drives.

The Hyperion cryocooler system consists of a Mechanical Pulse Tube (MPT) cooler with accelerometer electronics, Control Electronics Assembly (CEA), and LVDT electronics. The cooler provides focal plane cooling via a thermal strap connected to the cold block of the cooler. The cooler rejects heat to a radiator panel. The mechanical cooler (as shown in Figure 2-4) includes a compressor whose flexure springs support a moving-coil linear motor that drives the compressor pistons. A balancer vibrationally cancels the force that this piston motion creates. LVDT sensors are used to measure the piston position and the balancer position, control the piston strokes and reduce vibration. An accelerometer, mounted on the outside of the compressor housing, provides the feedback responses for the vibration control algorithm in the drive electronics (CEA). The CEA contains three slice subassemblies, one for control (control slice), one for power conversion (conversion slice), and one for power amplifiers (power slice).

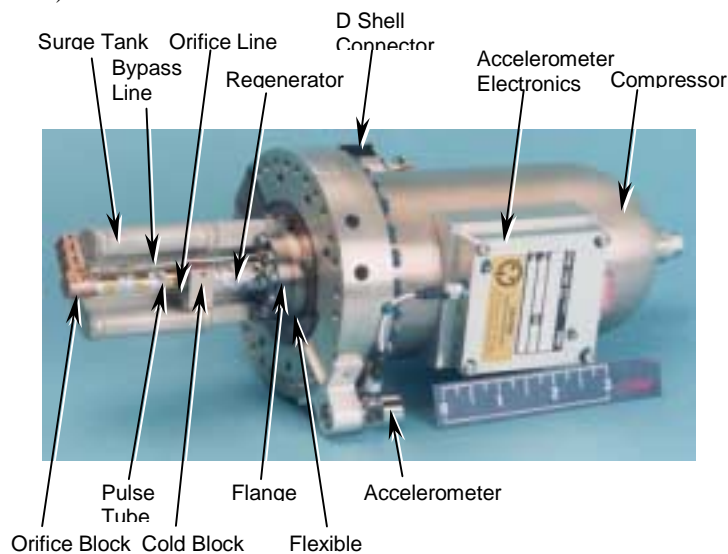


Figure 2-4 – Hyperion Cryocooler

3. HYPERION PERFORMANCE AND CHARACTERIZATION

The instrument was extensively characterized in the laboratory to verify performance and establish a radiometric calibration baseline. A majority of the testing was done with Hyperion in a thermal vacuum chamber (see Figure 3-1). A ground calibration system specifically developed to characterize and calibrate hyperspectral instruments was interfaced with the instrument. The system, called the Multispectral Test Bed (MSTB), consists of a monochromator whose output is used in one of two optical configurations (See Figure 3-2). Either the light uniformly illuminates a pinhole, slit or knife edge which is at the focus of an off-axis parabola reflector or the light illuminates a spectralon panel whose reflection is collimated by the same off-axis parabola. Figure 3-2 also shows a radiometer that is used as a transfer standard for absolute and NIST traceable sources/detectors. Typically, the light from the steering mirror is directed onto the transfer radiometer, or (when the radiometer is removed), into the Hyperion aperture through a vacuum chamber window. Details of the characterization measurements are given in Liao and Jarecke.¹

To more accurately assess and cross-verify the radiometric calibration of Hyperion the TRW Radiometric Scale Facility was used as part of the characterization process. This facility provides multiple paths to verifying the spectral radiance presented to the instrument under test. Light from a broadband, NIST-calibrated 1000 W FEL lamp was reflected from a white diffuser. This system was positioned immediately in front of the window in the thermal vacuum chamber and allowed to flood the Hyperion aperture and FOV. The output of this source was placed on a radiometric scale via several paths. First, the lamp radiance, diffuser reflectance, and geometry were established and a radiance of the diffuser was determined. Second, the radiance of the diffuser was measured with a calibrated Silicon trap detector. The spectral shape of the diffuser radiance was measured with a spectrally calibrated handheld spectrometer. Finally, a calibrated electrical substitution pyroelectric detector was used to characterize the diffuser radiance through narrow bandpass filters at centered several wavelengths across the 0.4 to 2.5 μm wavelength range. Each of these radiometric calibration techniques are traceable to

NIST standards or physical units via independent paths and the results agreed to $<2\%$. Details of the calibration technique and the results achieved are described in detail by Jarecke and Yokoyama.²

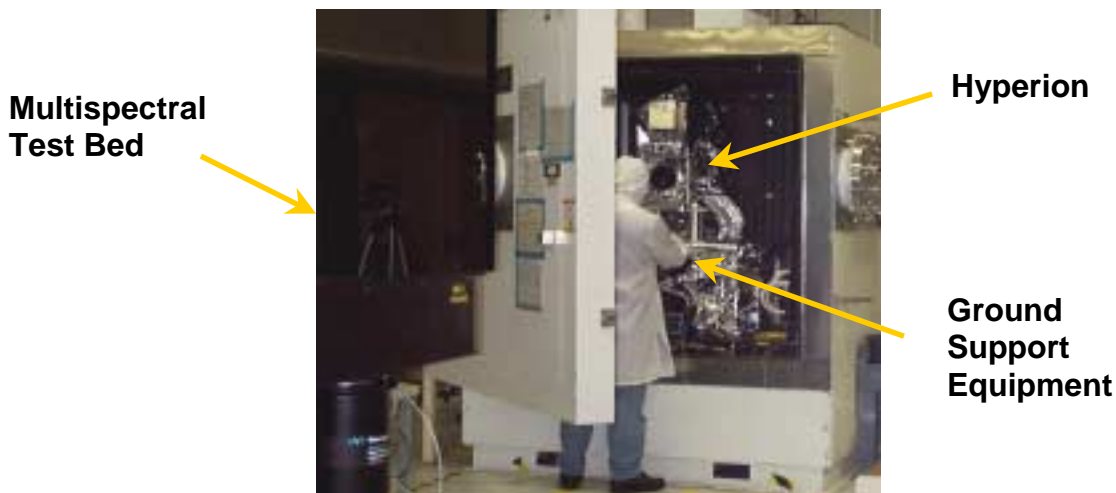


Figure 3-1 Hyperion in Vacuum Chamber

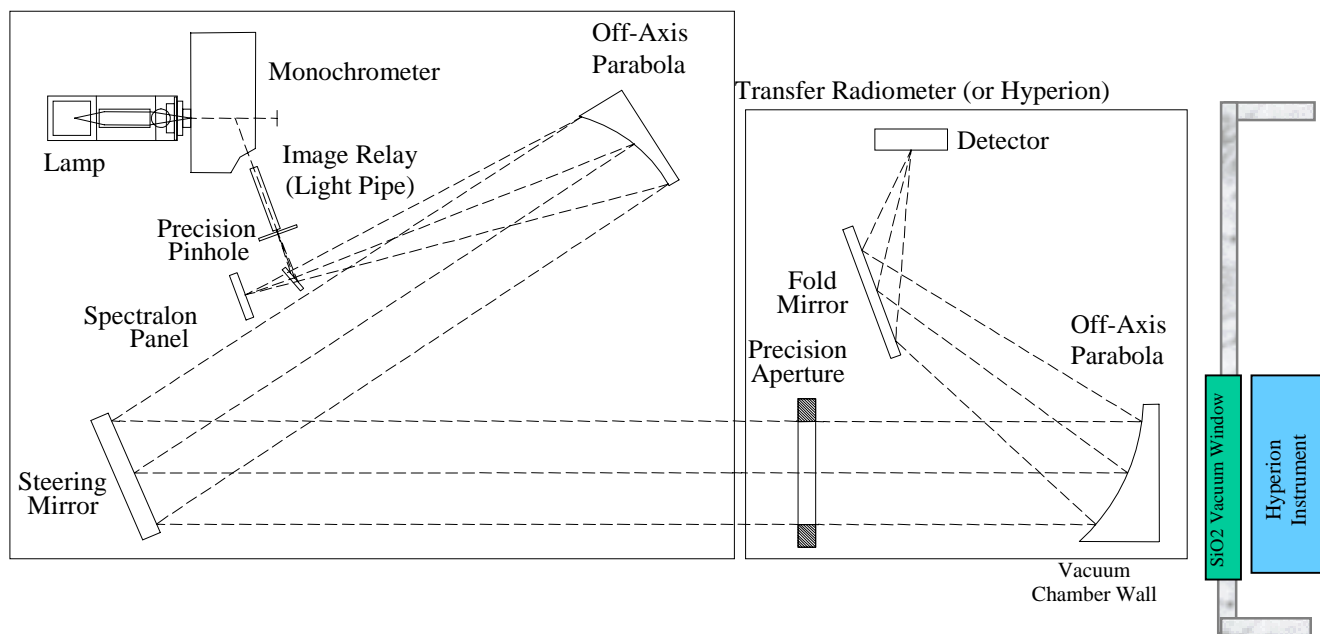


Figure 3-2 – Hyperion radiometric characterization with Multispectral Test Bed (MSTB)

The Hyperion MTF was measured using a knife edge technique. A slit technique was also used to cross-check the knife-edge MTF results. In the former, the image of a uniformly illuminated knife-edge was located at the focus of the parabolic reflector in the MSTB. The knife-edge was then imaged by the Hyperion optics onto the instrument image plane. The shape of the image was measured by the instrument directly. To eliminate discrete sampling effects the knife-edge image was stepped across the Hyperion field of view in fraction of a pixel increments using the steering mirror in the calibration facility. This resulted in data similar to that shown in Figure 3-4. These measurements were made at several locations in the crosstrack field of view and across the wavelength range of the instrument. The derivative of the knife edge data was calculated to yield the point spread function (PSF). Taking the Fourier transform of the PSF resulted in the modulation transfer function (MTF). The measurements showed MTF values at the Nyquist frequency between 0.26 and 0.30 as shown in the table of Figure 3-4.

The spectral response was characterized to determine band centers and bandwidths. This was done by creating a monochromatic extended source and moving the source spatially across the entire crosstrack field of view as well as scanning spectrally across the spectral range of Hyperion. A summary of the results is given in the tables of Figure 3-4 and Figure 3-5 for the VNIR and SWIR focal planes respectively.

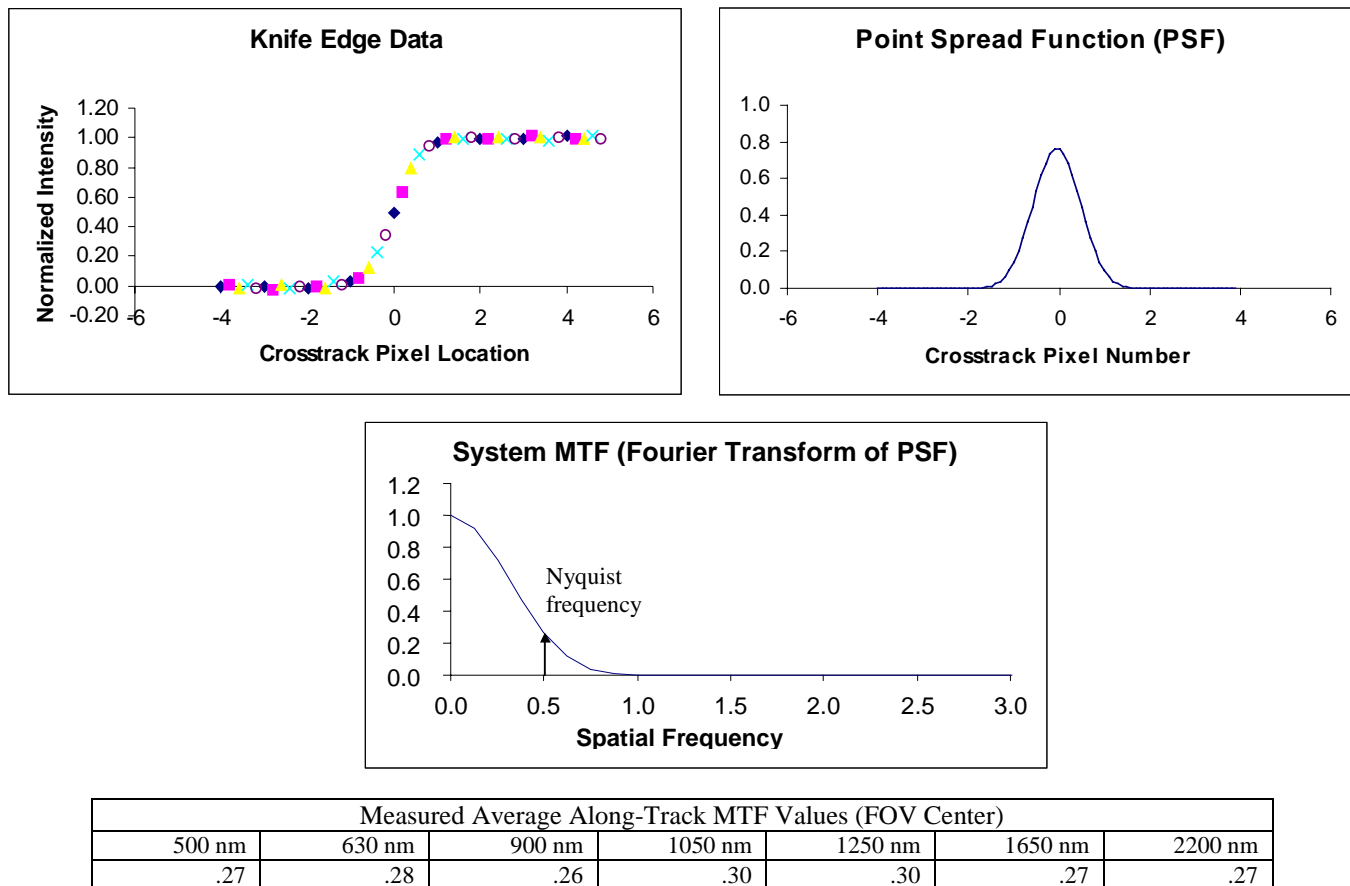


Figure 3-3 – The measured MTF of Hyperion for selected wavelengths

For any hyperspectral imager the spectral and spatial registration of the data are important to creating accurate data products. The two dimensions of this error source are called crosstrack spectral error and spatial co-registration of spectral channels (SCSC). The former is the variation in center wavelength as a function of crosstrack location. The crosstrack spectral error is evident in Figure 3-5. The latter error source was measured by imaging a broadband point target onto the Hyperion image plane at several locations across the crosstrack FOV. By stepping the point target in sub-pixel increments the spatial co-registration of spectral channels was measured to <0.05 pixel relative accuracy. The process and results are shown in Figure 3-6.

The signal-to-noise properties of Hyperion were determined by combining the measured spectral response function with a model of observation conditions. The conditions assumed in the model are a 60° Solar Zenith Angle and a 30% uniform Albedo. The resulting signal to noise performances is shown in Figure 3-7. The values shown by squares in the figure are the measured values during Hyperion characterization. The continuous curve is a model fit using the baseline conditions.

VNIR Channel Center Wavelengths (nm, accuracy +/- 0.5nm)					
Spectral Channel \ FOV #	13	31	40	48	57
6	477.4	656.5	753.6	834.3	925.4
71	478.5	657.5	754.1	834.9	925.1
136	478.0	656.8	753.7	834.4	925.3
196	476.8	655.7	752.8	833.4	924.4
251	475.1	654.6	751.3	831.9	922.8

VNIR FWHM of Spectral Response Functions (nm)					
Spectral Channel \ FOV #	13	31	40	48	57
6	11.2	10.5	10.6	11.1	11.1
71	11.6	10.4	10.9	11.3	11.3
136	11.3	10.3	10.7	11.3	11.3
196	11.4	10.2	10.7	11.4	11.3
251	11.3	10.2	10.6	11.3	11.2

Figure 3-4 – The spectral response functions for visible and near infrared wavelengths.

SWIR Channel Center Wavelengths (nm +/- 0.5nm)					
Spectral Channel \ FOV #	27	57	87	126	156
6	2314.1	2012.2	1711.2	1314.3	1013.3
71	2314.2	2012.1	1711.4	1315.2	1013.2
136	2314.0	2012.2	1711.6	1315.1	1013.2
196	2313.9	2012.1	1711.6	1315.1	1013.2
251	2313.7		1711.1	1314.2	1012.9

SWIR FWHM of Spectral Response Function					
Spectral Channel \ FOV #	27	57	87	126	156
6	10.4	10.6	11.6	10.6	10.7
71	10.5	10.8	11.4	10.6	11.1
136	10.4	10.9	11.8	10.8	11.2
196	10.5	11.1	11.6	10.8	11.2
251	10.2		11.3	10.6	11.1

Figure 3-5 – The spectral response functions for shortwave infrared wavelengths.

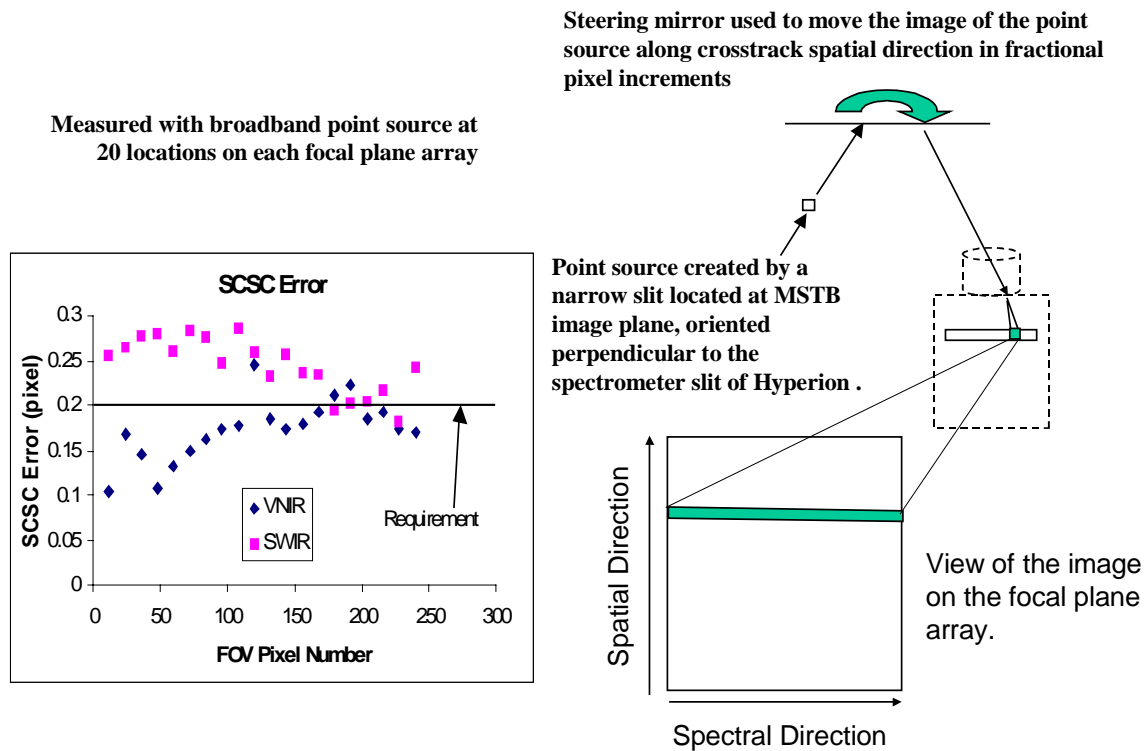
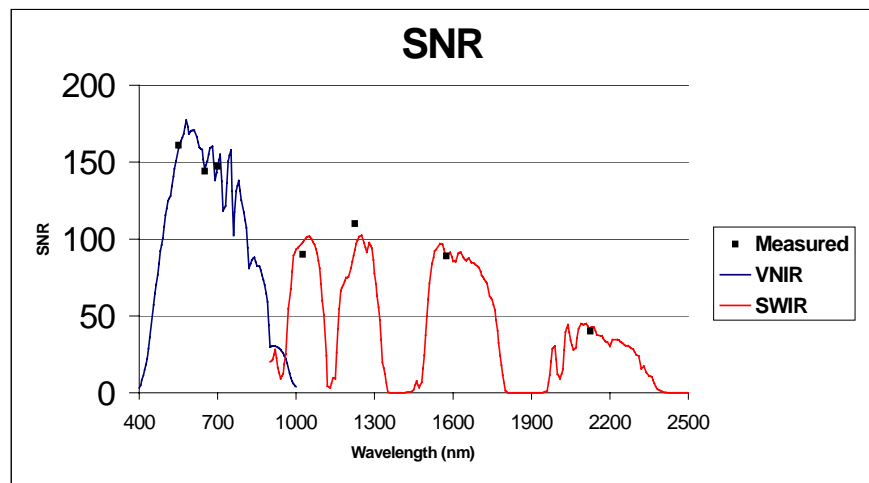


Figure 3-6 – The spatial co-registration of spectral channels (SCSC).



Hyperion Measured SNR						
550 nm	650 nm	700 nm	1025 nm	1225 nm	1575 nm	2125 nm
161	144	147	90	110	89	40

Figure 3-7 – Signal to Noise characteristics of the Hyperion Instrument.

4. HYPERION DATA PROCESSING

Data from Hyperion is stored on-board the spacecraft in a solid-state recorder. The data is downlinked and transmitted to GSFC for Level 0 processing. This processing includes removal of transmission artifacts and reordering of the data formats. The VNIR and SWIR data files are combined to provide a single image file (“raw imagery”). This and the flight data (housekeeping data) and ancillary data form a complete Level 0 data set. (See Figure 4-1) The data is transmitted to TRW for assessment and Level 1 radiometric calibration. Radiometric calibration formats the image and applies a radiometric calibration based on coefficients derived from both laboratory and on-orbit calibration data. The ancillary data is converted into engineering units to facilitate their later use. The different data types (image, metadata and ancillary data) are then combined into a standard data set and subject to a quality analysis. The data in the form of “cubes”, whose images cover 20km along track and 7.5km across track, are put into HDF format and transmitted to NASA GSFC for archiving during the mission life.

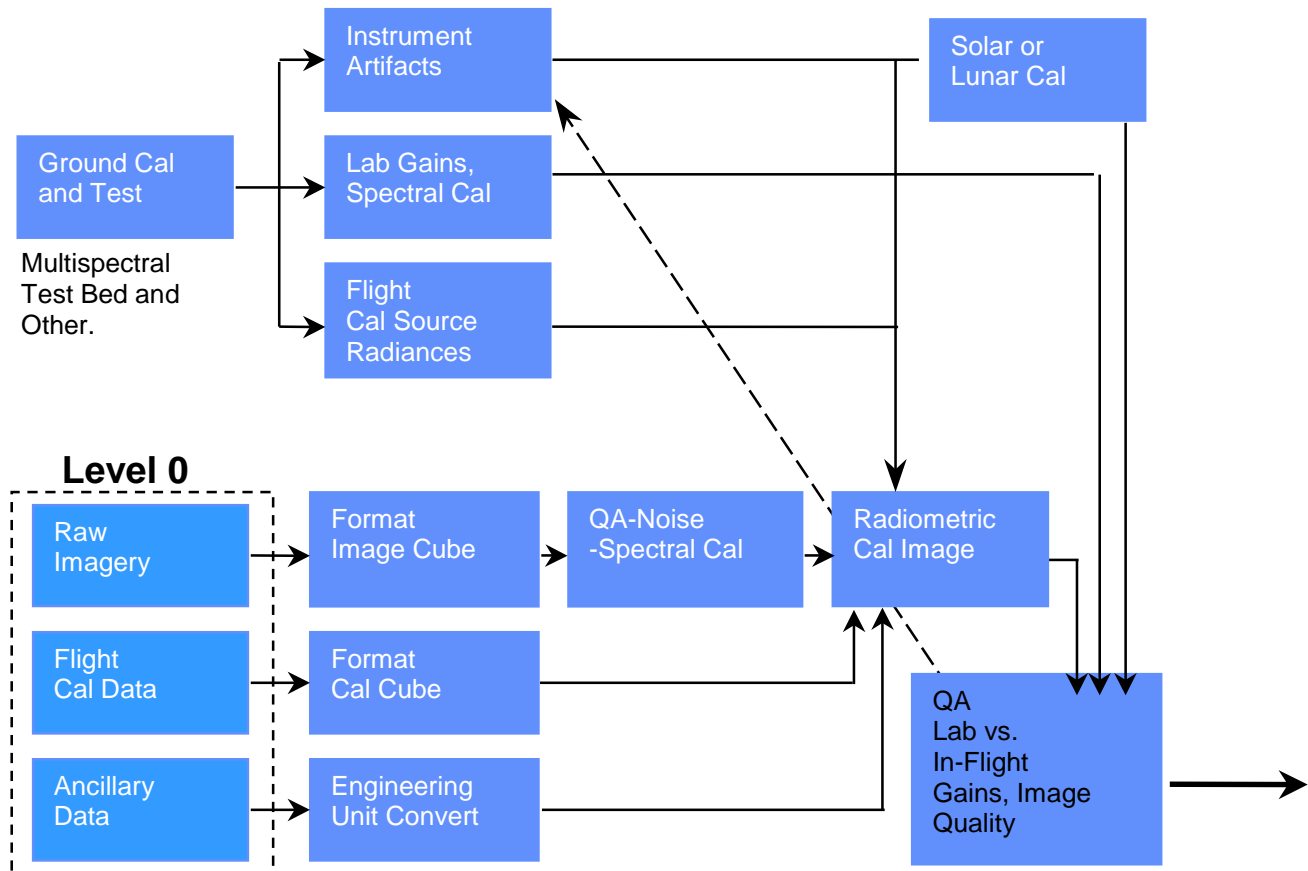


Figure 4-1 – Image data is combined with external data sets to provide a Level 1 radiometrically corrected image in HDF format.

5. OPERATIONS

EO-1 will be placed in an orbit that provides for “formation flight” with Landsat 7, Terra and the Argentine SAC-C. The EO-1 Mission will be launched on a Delta 7320 from Vandenberg Air Force Base in late 2000. EO-1 will fly in a 705km circular, sun-synchronous orbit at a 98.7 degree inclination. This orbit allows EO-1 to match the Landsat-7 orbit within one minute, and collect nearly identical images for later comparison on the ground.

During Early Orbit Checkout EO-1 eight data collections will be taken per day. A data collection event (DCE) includes external image data and the internal calibrations needed to support them. The external image may be for application assessment or calibration including ground calibration, lunar calibration, or solar calibration. A typical DCE will include a dark calibration, an imaging data collection, a dark calibration, a light calibration and a final, dark calibration. Lunar calibration is planned once per month; solar calibration is planned once per week.

Standard image sizes have been developed to facilitate data processing. For the Hyperion, an image, or cube, consists of 660 frames of data (19.8 Km long by 7.5 Km wide) and takes about 3 seconds to collect; an image equivalent to a Landsat scene is nine cubes. Data collection of longer images is possible for special requirements. The spacecraft is capable of a 22-degree roll angle that permits viewing a Landsat swath adjacent to the ground track swath. With this side-look capability, a given target on the Earth's surface can be imaged up to 5 times during the 16-day orbital ground track repeat. In this case, the angles of observation would be different because of the spacecraft roll required.

Hyperion on-orbit characterization is scheduled for the first sixty days after launch. During the first 20 days of this period, the instrument will be outgassed and activated. A calibration check will include internal lamps, solar collections and lunar imaging. Following completion of spacecraft related checkout for pointing and jitter, a full comparison with preflight baseline data will be done.

A series of calibration and reference sites in various regions of the earth will be used for the checkout. Long term Reference sites have also been identified and are relatively large in area with few features, minimal vegetation, and consistently minimal cloud cover. The purpose of these sites is to provide a scene that can be imaged once or twice a month over the course of a year to monitor any changes or drift in instrument performance. Reference sites have also been selected in northern Africa and Australia to accommodate a launch in late Fall, 2000.

In addition, several radiometric calibration sites have been selected in Australia, North America and Africa. All of these sites include some level of ground instrumentation for collecting a variety of concurrent information, including surface radiation, temperature, and atmospheric conditions. In some cases, arrangements have been made for obtaining ground truth measurements via airborne underflight coincident with satellite overflight using either the AVIRIS or other airborne instruments. Some locations, e.g., the Stennis calibration site, offer the opportunity to image a field in which an array of well-characterized radiometric materials has been deployed. Other sites have been selected for use in characterizing modulation transfer function (MTF), ground sample distance (GSD) (e.g., include San Francisco Bay and Iowa farm roads), stray light and dynamic range (e.g., Mauna Kea, and Lake Argyle (Australia)), and spectral characteristics (e.g., Mt. Fitton (Australia) and Cuprite (Nevada)).

Active calibration has been proposed to provide a precision means of measuring several instrument performance characteristics while on-orbit. Nighttime imaging of an array of xenon searchlights offers a unique opportunity for on-orbit assessment of EO-1 instrument co-alignment, MTF, GSD, spectral characteristics, stray light as well as providing data for geo-referencing. Experimental plans include deploying an array of high-power (7kw each) xenon searchlights in a known pattern. The searchlights are spaced at increasing intervals to accommodate the disparate fields-of-view and GSDs of the three EO-1 instruments. Using GPS, the searchlights can be located within 1 m of the desired position to provide geo-referencing, GSD, and geodetic information. Selection of a dry lakebed in the high desert of southern California as the deployment site provides a relatively large, flat, dark background for night imaging. The searchlights would be pointed at the satellite for nadir and off-nadir images, but no satellite tracking is planned. The spot diameter is ~11km at EO-1 orbital altitude.

A science team has been selected by NASA to support the technology validation objectives of the EO-1 mission. This team has two objectives: first, support the calibration and further characterization of Hyperion following the on-orbit check out and second, assess the value of space-based imaging spectroscopy for earth science missions. A broad range of applications research will address the utility of hyperspectral data for assessing land cover/land use, mineral resources, coastal processes and other earth and atmospheric processes. These are a total of 31 science teams with worldwide representation. Detailed information is available from the EO-1 website: <http://eo1.gsfc.nasa.gov>. In addition, coordination with Landsat and Terra operations could provide unique data sets for inter-comparison with ETM+, Aster, Modis and other instruments.

6. ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of the NASA Goddard Space Flight Center and the EO-1 team for their support on the Hyperion Program Contract No. NAS5-98161. This work was supported by the Hyperion test team including Glenn Brossus, Pam Clancy, Miguel Figueroa, Mark Frink, John Godden, Darrell Gleichauf, and Momi Ono, and who bore the brunt of the long hours of procedure execution and quick look data validation.

7. REFERENCES

1. Lushalan Liao, Peter Jarecke, "Radiometric Performance Characterization of the Hyperion Imaging Spectrometer Instrument", *Proc. Optical Science and Technology Symposium, Earth Observing Systems V*, SPIE 1435, (2000)
2. Peter Jarecke, Karen Yokoyama, "Radiometric Calibration Transfer Chain from Primary Standards to the End-to-End Hyperion Sensor", *Proc. Optical Science and Technology Symposium, Earth Observing Systems V*, SPIE 1435, (2000).